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Hazard assessment during caldera unrest at the Campi Flegrei, Italy: a contribution from gravity–height gradients

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Abstract

Hazard assessment and risk mitigation at restless calderas is only possible with adequate geophysical monitoring. We show here how detailed long-term micro-gravity and deformation surveys may contribute to hazard assessment at the Campi Flegrei caldera (CFc) in Italy by evaluating gravity–height change ($\Delta g/\Delta h$) gradients obtained during ground inflation and deflation between 1981 and 2001. Such gradients provide a framework from which to assess the likelihood and type of volcanic eruptions. Our new analysis of unrest at the CFc allows us to separate ‘noise’ during the gravity survey from the signal of deep-seated magmatic processes. This facilitates identification of the dynamics within the magma reservoir beneath the CFc. We found that magma replenishment during rapid uplift between 1982 and 1984 was insufficient, probably by one to two orders of magnitude, to trigger an eruption similar to the 1538 Monte Nuovo eruption, the most recent volcanic eruption within the CFc. Furthermore, our interpretation of $\Delta g/\Delta h$ gradients for the ongoing period of deflation since 1984 suggests that eruptive volcanic activity is not imminent. Short periods of minor inflation associated with large gravity changes since 1981 are interpreted to reflect noise, which to some degree is probably due to sub-surface mass/density changes within shallow hydrothermal systems beneath the CFc, indicating no risk of eruptive volcanic activity. We propose that monitoring $\Delta g/\Delta h$ gradients at restless calderas is essential as a caldera develops from a state of unrest to a state where volcanic eruptions have to be anticipated. Adoption of this method for the several tens of restless calderas world-wide will provide early warning of changes in or increase of activity at these supervolcanoes.

Author Keywords: caldera unrest; hazard assessment; gravity; deformation; Campi Flegrei

1. Introduction

World-wide, more than 100 calderas underwent periods of unrest during the second half of the 20th century [1]. Among them are the caldera complexes of Rabaul (Papua New Guinea), Yellowstone (USA), Long Valley (USA), Kilauea (USA) and the

Campi Flegrei (Italy), all of which have been intensively monitored with techniques including deformation and micro-gravity surveys during periods of inflation and deflation (see [2] for a compilation). Caldera-forming eruptions account for the most violent volcanic events recorded in Earth's history [3]. At the Campi Flegrei, for example, such eruptions [4 and 5] generated significant volumes of material that, if erupted at the present time, would pose serious threats to life and property on both local and global scales. Monitoring such restless calderas is an essential means to assess hazards and mitigate risks during potential volcanic crises [6].

Here, micro-gravity measurements may contribute in assessing sub-surface processes beneath caldera-related volcanic centres [2, 7 and 8]. Such gravity surveys are conventionally carried out in order to relate gravity changes (Δg) with elevation changes (Δh) as a means of inferring sub-surface mass/volume changes from gravity residuals [9]. Gravity–height data have been shown to be of value in determining precursors to volcanic activity [2]. In this communication, we apply gravity–height models published recently by [10, 11 and 12] in order to contribute to volcanic hazard assessment during unrest at the Campi Flegrei caldera (CFC), based on previously unpublished gravity–height data obtained between 1981 and 2001.

2. The interpretation of gravity–height gradients

Gravity and height changes are theoretically inversely correlated. A positive change in elevation (inflation) results in net gravity decrease, expressed as the free-air gravity gradient (FAG). At the CFC this gradient has been measured and found to be $-290 \pm 5 \mu\text{Gal/m}$ [9]. $1 \mu\text{Gal} = 10^{-8} \text{ m/s}^2$.

Deformation at active volcanoes can be interpreted in terms of the structural response of the edifice to sub-surface volume changes caused by mass/density changes. A simple mathematical concept developed by [13] enables the amount of surface deformation due to a sub-surface volume change to be quantified. It has been shown that the Mogi model fits many data sets from deformation surveys at calderas and provides constraints on sub-surface magmatic processes (e.g., [7, 9, 14 and 15]), in spite of its rather simplistic assumptions (see [12]). At the CFC, the geometry of a slab rather than a point source has been shown to be equally satisfactory [16]. Although non-linear gravity–height relationships have also been found at several active volcanoes, the relationship is typically linear at calderas in a state of unrest [2].

The observed linear gradients either follow or deviate from end-member model or theoretical gradients such as the FAG. The FAG arises simply due to elevation changes, while the Bouguer corrected free-air gravity gradient (BCFAG) arises because of displacements of density boundaries within the source of inflation/deflation [10 and 11]. For earlier data sets from the inflationary crisis at the CFC in the 1980s, [9 and 17] modelled the gravity data with a source density of 2500 kg/m^3 .

Here, we revisit the source density beneath the CFC by taking into account its dependence on composition, temperature, volatile content and pressure. Data compiled by [18] show that magmas erupted during the last 12 kyr have been gradually becoming more felsic. Indeed, the magma that fed the Monte Nuovo

eruption less than 500 years ago was among the most evolved ever erupted at the Campi Flegrei. The average composition erupted since 12 ka corresponds to a trachyte, whereas that erupted during the last 4.8 kyr represents a trachy-phonolite (Table 1). Pressure–volume–temperature models permit the establishment of an equation of state enabling the determination of melt densities as a function of those compositions erupted over the last 12 kyr at the Campi Flegrei. Chemical compositions of eruptive products as well as partial molar volumes (V_i), thermal molar expansivities (dV_i/dT) and molar compressibilities (dV_i/dP) of oxide components (subscript i) using data presented by [19, 20, 21, 22, 23 and 24] are compiled in Table 1. Liquid volumes (V_{liq}) are calculated via:

$$V_{liq}(T,P,X_i)=\sum X_i[V_{i,Tref}+dV_i/dT(T-T_{ref})+dV_i/dP(P-P_{ref})] \quad (1)$$

and liquid densities (ρ_{liq}) via:

$$\rho_{liq}=\sum X_i M_i / V_{liq}(T,P,X_i) \quad (2)$$

where X_i is the mole fraction and M_i is the molar mass. T_{ref} and P_{ref} are constant reference conditions as specified in Table 1.

Application of the models gives a reference melt density of $2350 \pm 120 \text{ kg/m}^3$ for temperatures between 993 and 1033 K, pressures between 0.1 and 0.13 GPa and magmatic water contents of 2–4 wt%. These are the expected conditions of the magma intrusion thought to be responsible for the latest caldera unrest at the CFC [17]. The water contents represent a conservative estimate, based on data on loss on ignition [5] and melt inclusions from [25]. The temperature estimate is based on results presented by [26]. For a point source geometry the resultant BCFA G_p at the CFC is $-224 \text{ } \mu\text{Gal/m}$ [13 and 27] and for an infinite slab geometry the BCFA G_s is $-192 \text{ } \mu\text{Gal/m}$ [27 and 28]. Both values are reported with an error of 4% based on an assessment of errors of the FAG determination and the source density estimate [11 and 12].

Rymer and Williams-Jones [10], Williams-Jones and Rymer [11] and Gottsmann and Rymer [12] have presented two models for interpreting $\Delta g/\Delta h$ gradients in terms of sub-surface mass/density changes at restless calderas. Both models aim to identify physico-chemical processes beneath caldera volcanoes and provide a geological framework from which to forecast volcanic activity and to assess volcanic hazards as a caldera volcano evolves from a state of dormancy through unrest to eruptive volcanic activity.

Fig. 1 illustrates both models: the right-hand side of the figure represents caldera inflation and the left-hand side represents caldera deflation. Once the effects of any changes at the surface (lava flows, landslides, etc.) have been removed, $\Delta g/\Delta h$ gradients plotting in any of the four quadrants of Fig. 1 must be interpreted as sub-surface mass and/or density changes. The four quadrants may be split into six (I–VI) regions, each reflecting specific sub-surface mass/density changes described in full in [10, 11 and 12]. Density increases or decreases need to be interpreted relative to the reference density given above.

In this study, we focus on the implication of measured $\Delta g/\Delta h$ gradients on volcanic hazard assessment based on evaluation of magma reservoir dynamics using new data from the CFc.

3. Geological setting and history of recent deformation at the Campi Flegrei caldera

The Campi Flegrei, Italy is dominated by a resurgent nested caldera resulting from two main collapse events related to the formation of the 37 ka Campanian Ignimbrite and the 12 ka Neapolitan Yellow Tuff [5 and 29]). The CFc (Fig. 2) comprises both submerged and continental parts on the western portion of the Bay of Naples and appears to have undergone resurgence since 10 ka ([30]; Fig. 2). Post-caldera volcanic activity has been mainly explosive and has migrated with time towards the centre of the caldera. The latest eruption occurred in 1538 during which the Monte Nuovo scoria cone was generated [31]. Although undergoing a period of subsidence since at least Roman times [32], short periods of uplift occurred in the early 1500s [31] and during bradyseismic crises since 1969 [33]. The latest periods of tumescence (1970–72 and 1982–84) resulted in a net uplift of 3.5 m. Results from geophysical investigations [34] and drilling [35] suggest that a shallow magma chamber resides beneath the CFc with its top at 3–4 km depth.

The town of Pozzuoli is situated in the centre of the area affected by uplift and deflation since 1981 (Fig. 2). The spatial pattern of deformation within the CFc is concentric around Pozzuoli (the area of maximum vertical deformation; mvd) with a radius of 6–7 km (Fig. 2). The deformation pattern associated with inflation and deflation at the CFc has been modelled and interpreted by various authors; most investigators suggest a source of volume change located at a depth of about 3 km, a few hundred metres east of the city of Pozzuoli (see [17] for a compilation). Berrino et al. [9], Dvorak and Berrino [16] and Corrado et al. [36] identified a shallow magma intrusion beneath the caldera as a possible source of the volume changes. Other authors [37] associate the hydrothermal system at the Campi Flegrei with the major source of deformation and pressure increase.

4. Gravity network and gravity–height data processing

At present, the gravity network at the CFc (Fig. 2) consists of 17 stations. The gravity stations are linked to the absolute gravity stations located in Naples [38] and the Accademia Aeronautica close to the Solfatara craters [39] and all are located at precise levelling benchmarks.

Gravity measurements have been carried out using two LaCoste and Romberg model D gravity meters (numbers 62 and 136), calibrated against the Troia–Mattinata base-line over a range of about 200 mGal [38 and 40]. This check provided a correlation between the two gravity meter readings. The relationship obtained is $\Delta g(D136) = (0.99872 \pm 0.00014) \Delta g(D62)$.

In addition, gravity meters have been calibrated periodically at the Bureau International de Poids et Mesures (BIPM) at Sèvres-Paris [41]. During the last calibration in 1994, the differences obtained between readings from all participating gravity meters were in the range $\pm 2 \mu\text{Gal}$ to $\pm 5 \mu\text{Gal}$. Earth-tide and air pressure effects were removed from the raw gravity data and the gravity differences between each pair of stations were obtained by a least square adjustment. The uncertainty of the gravity differences is estimated at less than $10 \mu\text{Gal}$.

Tide gauges, precise levelling and most recently GPS have been employed to monitor deformation at the CFC. Measurement errors and errors introduced by geoid corrections result in an uncertainty on the value of Δh at each benchmark of typically less than 1 cm.

Stations located in the area of maximum deformation had a time lag between the gravity and levelling measurements during rapid inflation. In these cases, the height changes were computed through a linear regression to elevation changes continuously monitored at the tide gauge station of Pozzuoli Harbour and the elevation changes measured by levelling surveys at the gravity stations [42]. The computed relationships show a satisfactory agreement. The only disagreement was observed in 1993 due to a larger vertical movement recorded by tide gauges [42]. If this is not taken into account the Δh computed from tide gauges is reliable to within a few centimetres. Examples of the relationship obtained for computing elevation changes at the gravity benchmarks from tide gauge data are reported in [17 and 42].

In order to obtain $\Delta g/\Delta h$ gradients, the average values for Δg and Δh for each station for each survey are used. After the identification of apparent background noise in gravity and deformation readings of $\pm 20 \mu\text{Gal}$ and ± 0.01 m, respectively, we performed a noise correction as outlined in Section 6. This involved generating four additional data points ($\pm 20 \mu\text{Gal}$ and ± 0.01 m) for each measured gravity–deformation data point; noise-dominated readings were eliminated at this stage. Linear regressions to the larger dataset yielded more reliable $\Delta g/\Delta h$ gradients since the errors induced by noise are accounted for. $\Delta g/\Delta h$ gradients which represent least squares fits and associated fit standard errors were then computed for each single identifiable deformation period at its respective station.

5. Results

The observed gravity changes are well correlated with the elevation changes, both during the overall periods of inflation (1982–84) and during periods of deflation (1985–2001). Removing from the gravity changes the effect of the elevation changes leaves significant gravity residuals indicating net sub-surface mass redistribution. The temporal relationship of the gravity and elevation changes and of the gravity residuals at all stations is shown in Fig. 3. Fig. 3A shows the data obtained from stations at the centre of the caldera (the area characterised by 100–25% mvd; see also Fig. 2).

Data collected from stations situated within the area characterised by less than 25% mvd are shown in Fig. 3B. For the interpretation of $\Delta g/\Delta h$ gradients, only data obtained at stations situated in the area within which 25–100% of the maximum deformation occurred are considered, since the signal to noise ratio is most

favourable. Gradients obtained for stations outside the area of 25% mvd are predominantly characterised by minor amounts of deformation yet large changes in gravity ($\Delta g/\Delta h$ gradients of $>-1000 \mu\text{Gal/m}$; Table 2).

Observed gravity changes in the area of 100–25% mvd are well correlated with elevation changes, both during the overall periods of inflation (1982–84) and during periods of deflation (1985–2001). $\Delta g/\Delta h$ gradients obtained for each station within this area during periods of inflation and deflation are reported in Table 2. This detailed discrimination permits the precise identification of the spatial and temporal variation of sub-surface processes responsible for ground movement at the CFC. Furthermore, each $\Delta g/\Delta h$ gradient may be evaluated in terms of the key in Fig. 1. At Bagnoli, for example, the gradient obtained during deflation between May 1987 and March 2000 is $-143 \mu\text{Gal/m}$ (Table 2), which plots below both the BCFAG and FAG. It can be seen from Fig. 1 that this gradient falls into region IV and thus reflects both sub-surface mass and density decrease.

The detailed analysis of the gravity–deformation data allows for the separation of different episodes of vertical displacement and their associated gravity changes. We show later that the identification of these episodes is essential for the interpretation of the $\Delta g/\Delta h$ gradients in terms of sub-surface processes and thus for volcanic hazard assessment during caldera unrest.

Deflation between 1981 and 1982 shortly before the onset of rapid inflation follows gradients in excess of $-800 \mu\text{Gal/m}$ (stations Arco Felice, Bagnoli, Via Campana) with fit standard errors between 20 and 30% (Table 2). At Serapeo the gradient of $-195 \mu\text{Gal/m}$ shows an error of almost 200%.

$\Delta g/\Delta h$ gradients determined during the period of inflation January 1982 and May 1985 at stations situated within 100–25% mvd (Fig. 4; Table 2) vary between $-163 \mu\text{Gal/m}$ (Via Campana) and $-224 \mu\text{Gal/m}$ (Solfatara). The gradients generally have fit standard errors of less than 14% with the exception of the gradient obtained at station Arco Felice, which shows an error of 20%. The average $\Delta g/\Delta h$ gradient obtained during inflation is $-191 \pm 19 \mu\text{Gal/m}$.

A peculiar feature during the overall pattern of deflation between 1985 and 2001 (Fig. 3) is the presence of short periods of inflation and deflation of a few millimetres to a few centimetres (e.g., at La Pietra between March and May 1994; Table 2). The most recent period of small inflation reported here occurred between March 2000 and March 2001. Gravity changes associated with this tumescence are of the order of tens of μGal . As a result, $\Delta g/\Delta h$ gradients between -800 and $-12500 \mu\text{Gal/m}$ (Table 2) are obtained. Such high gradients are recognisable at all stations of the network. However, their temporal and spatial characteristics do not show a uniform pattern; e.g., the short period of inflation between March and May 1994 is only recognisable at three of the eight stations located within 100–25% mvd (Table 2).

$\Delta g/\Delta h$ gradients determined during overall deflation between 1985 and 2001 (intercepted by short periods of minute inverted deformation; Table 2; Fig. 3) show more pronounced variations both spatially and temporally than gradients obtained during inflation prior to 1985. With the exception of the $\Delta g/\Delta h$ gradient for station Accademia Aeronautica, which is associated with a large fit standard error of more

than 100% and thus not further considered in the data analysis presented here, the respective $\Delta g/\Delta h$ gradients vary between -287 and $-113 \mu\text{Gal/m}$. These gradients have fit standard errors between 2 and 41%. The average fit standard errors obtained for the period of deflation are considerably higher than fit standard errors for the gradients obtained during rapid inflation (Table 2; Fig. 4). The average $\Delta g/\Delta h$ gradient obtained for deflation is $-168 \pm 35 \mu\text{Gal/m}$.

6. Interpretation and implications

6.1. Background noise and shallow processes

Large $\Delta g/\Delta h$ gradients ($> -800 \mu\text{Gal/m}$) are observed during both deflation and short periods of uplift before and after the 1982–1984 rapid inflation. Such gradients are especially characteristic of the area of less than 25% mvd (Table 2), where many vertical height changes are within the error of measurement (± 1 cm). Associated gravity changes are on average $\pm 20 \mu\text{Gal}$. Moreover, gravity–height changes often result in positive gravity gradients recorded for example at Via Napoli (Table 2).

Such gradients are difficult to interpret in terms of sub-surface mass/density changes. We therefore suggest that these gradients reflect noise during the gravity surveys within the CFc. This recognition allowed for the analysis of gravity–height measurements and provided the basis for a noise filter as outlined above.

Some stations give $\Delta g/\Delta h$ gradients between -450 and $-800 \mu\text{Gal/m}$ over time intervals of a few months to less than 2 years during both minor inflation and deflation. Similar $\Delta g/\Delta h$ gradients have been reported at other caldera centres such as Askja, Krafla and Kilauea (see [12] for a compilation). Such gradients have been interpreted as reflecting shallow processes (10–100 m depth) of hydrothermal activity (fluid migration) or dyke emplacement [14, 43 and 44]. Based on the lack of structural or geochemical evidence of shallow dyke emplacement during the period of overall deflation prior to 1982 and after 1984 which could be responsible for large gravity residuals during minor deformation [12], one must surmise that hydrothermal activity was the shallow sub-surface processes beneath the CFc. We therefore consider gravity gradients between -450 and $-800 \mu\text{Gal/m}$ as ‘noise’ probably associated with shallow hydrothermal processes. Gradients $> 800 \mu\text{Gal/m}$ are thought to reflect urban or other superficial noise within the CFc (Table 2). Thus we have not considered gradients in excess of $-450 \mu\text{Gal/m}$ for volcanic hazard assessment during inflation and deflation at the CFc.

6.2. Inflation

The average $\Delta g/\Delta h$ gradient of $-191 \mu\text{Gal/m}$ for stations situated within the area of 100–25% mvd during the period of rapid inflation between 1982 and 1984 is indicative of a sub-surface mass increase as it deviates from the FAG (Fig. 5).

Within error ($\pm 19 \mu\text{Gal/m}$) it follows closely the BCFAG_s ($-192 \pm 8 \mu\text{Gal/m}$). This has two implications: either (i) an overall sub-surface mass and density increase occurred assuming a Mogi point pressure source or (ii) a sub-surface mass increase but no

density change must be inferred if a slab geometry of the pressurised source is assumed.

Based on the evaluation of gravity residuals and the assumption of a pressurised point source, [9] and [17] suggested that a sub-surface mass increase of 2×10^{11} kg may have been caused by the injection of magma into the surrounding country rock at a depth of about 3 km between 1982 and 1984. Alternatively, [16] suggested that a rectangular planar sheet geometry might fit the data equally well.

Berrino [17] proposed that magma injection deduced from the gravity data is lateral with no or only a small upward movement, based on the evaluation of seismic and geochemical data [45 and 46]. A comparison of our magma density estimate with country rock densities presented by [34] for a depth of 3 km suggests that no or only a small density contrast between the injected magma and the surrounding rock would have existed. If this were indeed the case, our analyses would support a slab-like injection of magma beneath the CFc. Nevertheless, whatever source geometry is assumed (slab or point), our interpretation of the $\Delta g/\Delta h$ gradients suggests that the magmatic system beneath the CFc was replenished as new mass was added. A lateral outbreak of a new magma pocket into the surrounding country rock may have been caused by the injection of new magma into the reservoir. Whether the source density remained unchanged or whether a density increase occurred may not be unambiguously resolved. From the interpretation in Fig. 1, a volcanic eruption was unlikely to follow for both scenarios since a density decrease in the source (e.g., during vesiculation) is more likely to trigger a volcanic eruption [10, 11 and 12]. Indeed, no eruption occurred. Nevertheless, we discuss the mass injection between 1982 and 1984 as a possible trigger for eruptive activity in Section 6.3.

One limitation of the computation of the mass increase for the CFc during rapid inflation by [9] and [17] is the assumption of a purely elastic response of the surrounding country rock to the pressurisation of a point source. The assumption of elastic behaviour certainly has limited applicability in a volcanic environment with a long history of volcanic eruptions and the existence of long-lived magmatic reservoirs, such as the Campi Flegrei. It may therefore be more reasonable to assume a viscoelastic response of the country rock for the CFc. [47] modeled both gravity and displacement changes that occurred between 1982 and 1984 at the CFc employing a numerical solution for the anelastic response of the country rock. In their computation, they assumed an elastic half space overlain by a 3 km thick viscoelastic layered medium. Their model succeeded in reproducing the magnitude and pattern of both height and gravity changes, although a perfect match of the observed values was not achieved. Nevertheless, their calculated mass required for a magma intrusion at 3 km depth to induce the observed changes was 60% higher than that modelled by [9, 16 and 17], while the associated pressure increase was more than one order of magnitude lower [47]. It appears obvious that mass budgets computed for magma input in any long-lived volcanic environment assuming a purely elastic response of the surrounding medium may only be regarded as providing minimal estimates.

The mass increase computed for the CFc during rapid inflation by [9, 16 and 17] and [47] is about three and nine times higher, respectively, than the dense rock equivalent of the Monte Nuovo eruption in 1538 (6.3×10^{10} kg; calculated from [31]). An

inflation of up to 8 m was reported prior to that eruption ([31] and references therein; [48]).

Results presented by [49] suggest that a volcanic eruption may be triggered by a sub-surface volume increase (simple magma injection) that induces a pressure increase that exceeds the lithostatic pressure by an amount greater than the tensile strength of the magma chamber walls. During such an eruption, only about 0.1–1% of the total mass of magma inside a chamber is being erupted. The Monte Nuovo eruption appears not to have been primarily triggered by vesiculation inside a phonolitic magma reservoir (lack of explosivity, lack of pumice deposits [31]) but rather by a pressure increase due to mass injection. It is therefore reasonable to assume that if a pressure increase leading to a volcanic eruption at the CFc was purely due to a magma mass increase, this increase needs to be of the order of 10^{12} – 10^{13} kg at a depth of 3 km beneath the CFc. The mass input during 1982–1984 thus appears insufficient to trigger such activity.

Clearly, in the case of pressurisation being caused by magma vesiculation, an eruption may follow at a smaller-scale mass injection. The associated density change would, however, be recognisable in the gravity data, as observed at other volcanoes (e.g., [50]).

In terms of prolonged hazard assessment, one also has to take into account the potential mobility of silicate melts beneath the CFc. For a temperature of 1013 K and water contents between 2 and 4 wt%, the model presented by [51] gives shear viscosities between \log_{10} 6.1 and 4.6 Pa s for the melt composition of the Monte Nuovo eruption. The quoted temperature and water contents are estimates of the current magmatic conditions beneath the CFc reported in [26] and [52], respectively. Given such melt viscosities, one would suspect that new magma injection into country rock at shallow depths [53] is still a possible scenario for the future at the CFc.

6.3. Deflation

The average $\Delta g/\Delta h$ gradient determined for the period of deflation falls into region IV of Fig. 1 (cf. Fig. 5) and both mass and density decrease in the source have to be inferred. However, within its upper error limits the derived gradient follows the BCFA_G. Within the uncertainty of our fit, it appears uncertain whether the inferred mass change is also associated with a density change. Station Solfatara, which hosts an active superficial hydrothermal system, appears to have a $\Delta g/\Delta h$ gradient that is inconsistent with the other stations within 100–25% mvd (Fig. 4). Its gradient indicates a density increase but no mass change as it follows closely the FAG. It appears that although the general pattern during deflation of the CFc suggests sub-surface mass loss, at Solfatara the sub-surface mass distribution remained unchanged. If the gradient for Solfatara is disregarded, the average gradient during deflation becomes $-149 \pm 37 \text{ } \mu\text{Gal/m}$.

Berrino [17] suggested that about 50% of the mass gained in the source between 1982 and 1984 was lost between 1985 and 1987. After a period of relatively rapid deflation (cf. Fig. 3), the rate of deflation in the area of 100–50% mvd dropped to less than 17 mm per month, similar to the rate of deflation observed before 1969 [36]). If slow deflation was purely the result of the elastic response of the surrounding rock to the

slow cooling of the magmatic system beneath the CFc, the associated $\Delta g/\Delta h$ gradients should follow the FAG, since no mass change is involved. Except for station Solfatara this is clearly not the case in the general pattern of $\Delta g/\Delta h$ gradients during deflation since 1985 (cf. Fig. 4 and Fig. 5). It is noteworthy that $\Delta g/\Delta h$ gradients during deflation do not simply mirror gradients observed during inflation, in other words the process that induced inflation was not entirely reversed during the deflation period. This has two important implications: (i) the creation of voids has to be inferred if the source responsible for deflation is assumed to be the same as for inflation or (ii) a source different from that responsible for inflation (geometry and/or depth and/or density) may have to be considered. The latter needs to be further assessed by thorough forward modelling of the deformation and gravity data obtained during deflation since 1987.

In summary, the current pattern of overall deflation at the Campi Flegrei since 1985 through to 2001 and the associated $\Delta g/\Delta h$ gradients indicate continued relaxation of the magmatic system. The $\Delta g/\Delta h$ gradients do not coincide with any regions of Fig. 1 indicative of potential eruptive volcanic activity. Furthermore, none of the $\Delta g/\Delta h$ gradients are consistent with the notion that the system is developing towards a state where caldera collapse may result from mass drainage during deflation, quite in contrast to developments at Miyakejima volcano in Japan, where lateral magma drainage has recently resulted in catastrophic roof collapse [54].

7. Conclusions

We have shown that detailed analysis of $\Delta g/\Delta h$ gradients helps to identify sub-surface mass and/or density changes in order to assess the possibility of volcanic eruptions during caldera unrest at the Campi Flegrei. This evaluation contributed to infer magma dynamics within the reservoir responsible for inflation and deflation.

Based on our evaluation of the $\Delta g/\Delta h$ gradients during the period of rapid inflation between 1982 and 1984, the magmatic system beneath the CFc was replenished, but an explosive volcanic eruption was unlikely to occur. The current pattern of overall deflation at the Campi Flegrei since 1985 and its associated $\Delta g/\Delta h$ gradients indicate that eruptive volcanic activity or hazardous downsagging of the CFc that may develop into catastrophic roof collapse during magma withdrawal is at the present time unlikely. Continued relaxation of the magmatic system is the most reasonable interpretation of the data obtained. The evaluation of $\Delta g/\Delta h$ gradients associated with only minor or no deformation indicates the existence of shallow processes within the CFc that constitute ‘noise’ during long-term gravity surveys. Some of the noise may be produced by shallow mass/density variations in locally restricted, individual hydrothermal systems rather than by magmatic mass/density changes.

We have shown that long-term micro-gravity monitoring may reveal deeper insights into and discrimination of sub-surface processes beneath restless calderas. Such investigations will not only play an important role in determining when a caldera develops from a state of unrest to a state where volcanic eruptions have to be anticipated, but they will also provide a valuable means to assess associated volcanic hazards. It appears plausible to develop the current conventional micro-gravity surveys further towards the use of continuous gravity monitoring using a network of gravity meters endorsed by continuous deformation monitoring in order to improve

the temporal and spatial resolution of sub-surface mass/density beneath restless calderas. This would constitute a major contribution to real-time volcano monitoring. Towards this end, development of a new instrument is under way in our laboratory at the Open University.

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Figures and captions

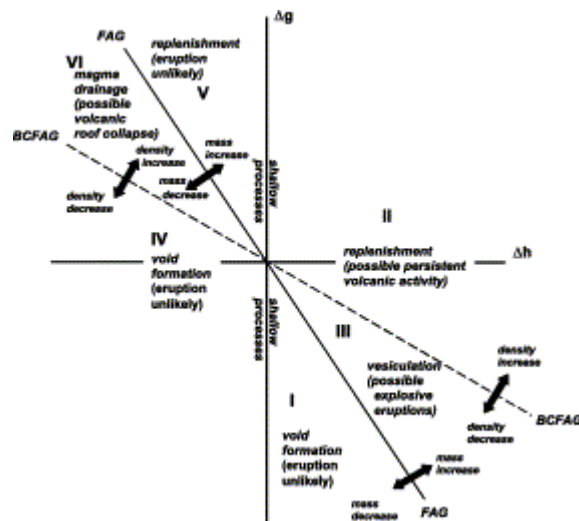


Fig. 1. The interpretation of $\Delta g/\Delta h$ data deviating from predicted gradients (FAG and BCFAG) in terms of their identification as possible precursors to volcanic activity. Six regions (I–VI) may be discriminated. If data plot in regions I or IV, both reflecting mass decrease and density decrease, volcanic eruptions are unlikely to occur as voids are created during this process. Data falling in regions II or V (mass increase/density increase) reflect replenishment of the magmatic system. Volcanic eruptions are unlikely to occur if the gradients plot in region V, due to the lack of overpressure. Region II may reflect potential persistent volcanic activity. Eruptions, if

they were to occur, are likely to be effusive and/or low-explosivity events due to the lack of significant pressurisation, i.e., vesiculation [11 and 12]. Data falling into region III during caldera inflation may be interpreted in terms of the input of new magma into an existing reservoir inducing vesiculation and pressure build-up, an important trigger mechanism for highly explosive eruptions, potentially associated with caldera formation. Data falling into region VI during caldera deflation indicate sub-surface density increase and mass decrease. One possibility is the lateral drainage of magma while new magma is being injected into the reservoir to an extent such that the overall sub-surface mass is decreasing. Another mechanism would be the downward collapse – downsagging – of the overlying country rock during lateral magma drainage associated with little or no magma replenishment. During both scenarios, continual downsagging may result in the creation of fractures as brittle failure occurs in the overlying country rock. Caldera formation may be the extreme end-member of such a process [12]. Gradients plotting along or close to the ordinate reflect shallow-seated processes such as magma and/or gas fluctuations within the feeder conduit [11], dyke emplacement close to the surface [12] or hydrothermal activity. Associated volcanic eruptions may be characterised by effusive and low-explosive events.

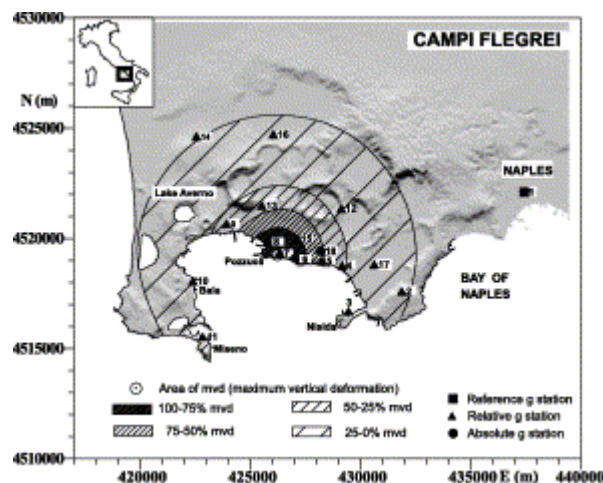
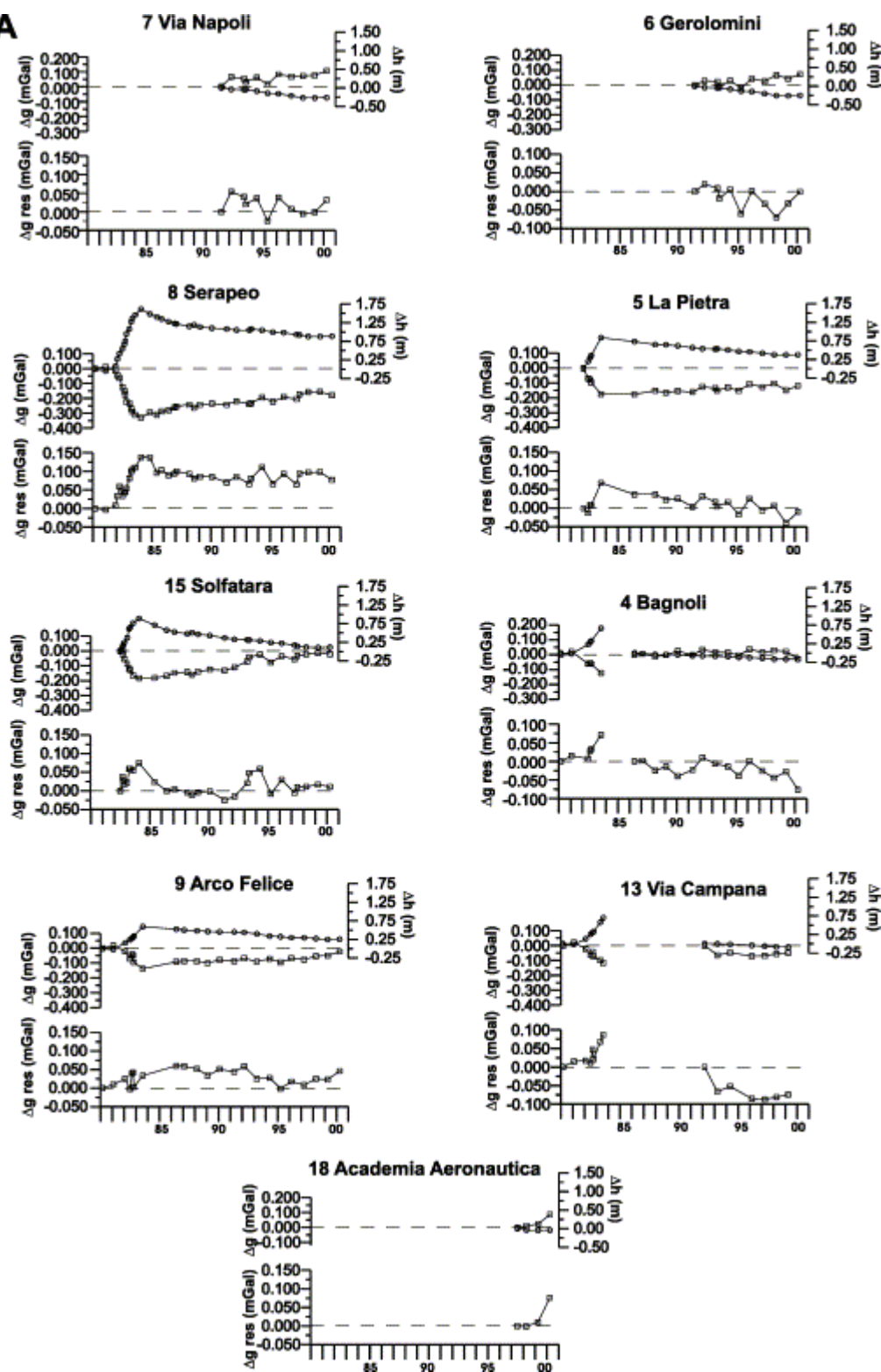


Fig. 2. The area of vertical deformation (hatched) during bradyseisms since 1972 at the Campi Flegrei, Italy superimposed on a digital elevation model. The area is divided into four sub-areas, which are represented by the percentage of maximum vertical deformation (mvd). Numbers depict the location of individual gravity stations (reference, relative and absolute): 100–75% mvd: 6-Gerolomini, 7-Via Napoli, 8-Serapeo, 15-Solfatara; 75–50% mvd: 5-La Pietra, 18-Accademia Aeronautica; 50–25% mvd: 4-Bagnoli, 9-Arco Felice, 13-Via Campana; <25% mvd: 2-Posillipo, 3-Nisida, 10-Baia, 11-Miseno, 12-Astroni, 14-Monte Ruscello, 16-Quarto, 17-Piazza Esedra.

A

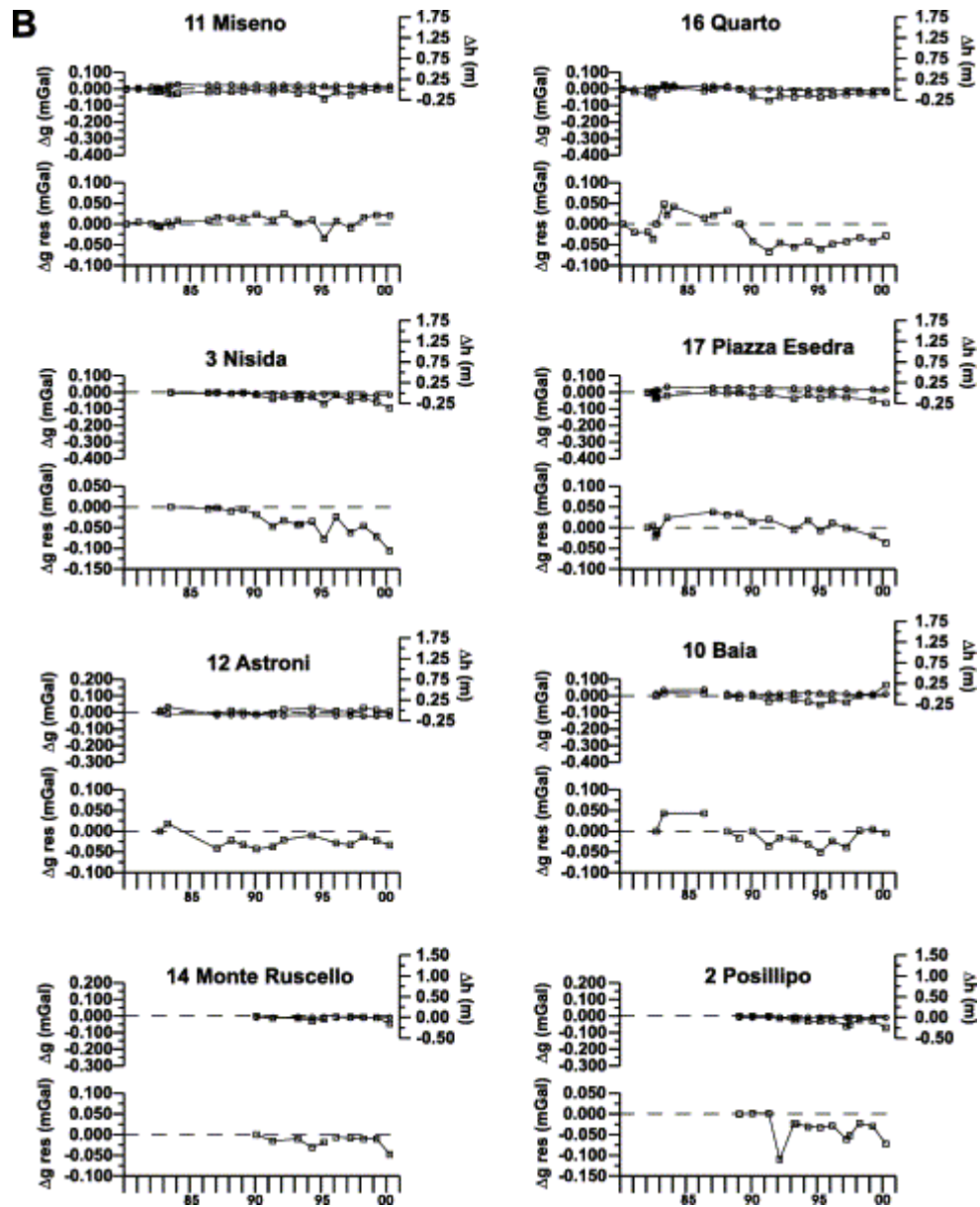


Fig. 3. (A) Gravity (Δg), height (Δh) and residual gravity (Δg res) changes measured at the CFc since 1981. Stations are situated within the area of 100–25% mvd. Circles refer to Δh and squares to Δg data. (B) Same as in A, but for stations situated within the area of less than 25% mvd.

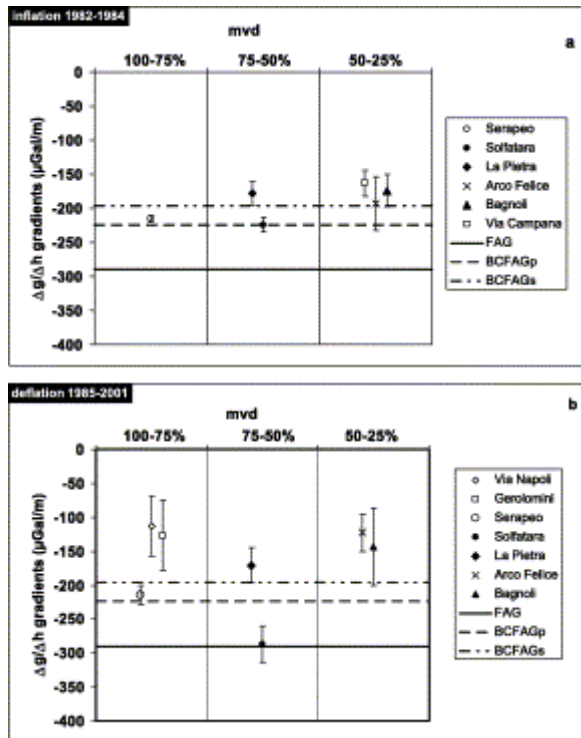


Fig. 4. $\Delta g/\Delta h$ gradients obtained at stations situated within the area of 100–25% mvd CFC during inflation (a) between 1982 and 1984 and during deflation (b) between 1985 and 2001. Both figures also include end-member gradients FAG, BCFAG_p and BCFAG_s. Data displayed in both graphs form the basis for the calculation of average gradients during inflation and deflation displayed in Fig. 5. See text for details.

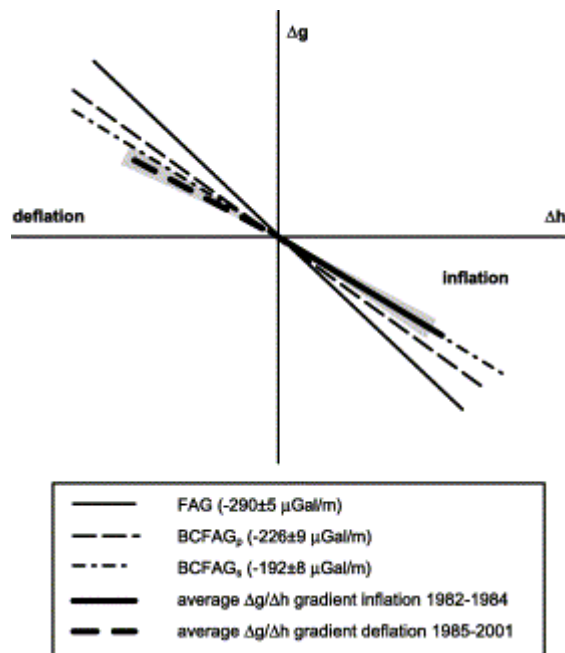


Fig. 5. The average $\Delta g/\Delta h$ gradients obtained during periods of inflation (solid bold line) and deflation (broken bold line) at the CFC. Error margins of the average values

are shown in grey. End-member gradients FAG, BCFAG_p and BCFAG_s for both periods are also displayed. The gradients may be interpreted according to Fig. 1.

Table 1

Average major oxide chemistry (wt%, anhydrous and normalised to 100%) of trachytic and trachy-phonolitic melts erupted over the last 12 kyr and 4.8 kyr at the Campi Flegrei, respectively including partial molar volumes, thermal expansions and compressibilities of respective oxide components

Oxide	Trachyte (wt%)	Trachy-phonolite (wt%)	V_i, T_{ref}^a (cm ³ /mol)	$(dV_i/dT)_{T_{ref}}^a$ (10 ⁻⁴ cm ³ /mol K)	$(dV_i/dP)_{T_{ref}}^b$ (10 ⁻⁴ cm ³ /mol bar)	$[(dV_i/dP)]/dT$ (10 ⁻⁷ cm ³ /mol bar K)
SiO ₂	60.7	62.3	26.9	0.00	-1.89	1.30
TiO ₂	0.5	0.4	23.16	72.40	-2.31	—
Al ₂ O ₃	19.2	18.2	37.11	-39.40	-2.26	2.70
Fe ₂ O ₃	4.3	3.0	42.13	26.20	-2.53	3.10
MnO	0.1	0.2	—	—	—	—
MgO	0.5	0.3	11.45	26.20	0.27	-1.30
CaO	2.7	2.0	16.57	29.20	0.34	-2.90
Na ₂ O	4.3	5.3	28.78	29.20	-2.40	-6.60
K ₂ O	7.5	7.4	45.84	119.10	-6.75	-14.50
P ₂ O ₅	0.3	0.8	69.03	-1.00	—	—
H ₂ O			22.9	94.6	-3.2	—

Chemical compositions are averaged values from results presented in [18]. Volume and thermal expansivity data are from [19, 20, 23 and 24], thermal compressibility data are from [21 and 22].

Table 2

$\Delta g/\Delta h$ gradients obtained from linear fits to gravity–height data at the CFc between January 1981 (1/81) and March 2001 (3/01)

Station (% mvd)	Observation period	Nature of deformation	$\Delta g/\Delta h$ gradient ($\mu\text{Gal/m}$)	Fit standard error (\pm ; $\mu\text{Gal/m}$)
100–25% mvd				
Via Napoli	4/92–3/94	<i>deflation</i>	–1381	117
100%	3/94–5/94	<i>inflation</i>	4400	69
	5/94–3/00	<i>deflation</i>	–113	44
	3/00–3/01	<i>inflation</i>	3000	39
Gerolomini	4/92–3/94	<i>deflation</i>	–606	89
100%	3/94–5/94	<i>inflation</i>	–7500	1600
	5/94–3/00	<i>deflation</i>	–127	52
	3/00–3/01	<i>inflation</i>	4142	867
Accademia Aeronautica	6/98–3/00	<i>deflation</i>	–497	742
100%	3/00–3/01	<i>inflation</i>	–10833	156
Serapeco	2/81–1/82	<i>deflation</i>	–195	390
100–75%	1/82–1/85	<i>inflation</i>	–215	5
	1/85–3/00	<i>deflation</i>	–215	14
	2/89–7/89	<i>inflation</i>	–639	42
	3/94–5/94	<i>inflation</i>	233	118
	3/00–3/01	<i>inflation</i>	–2400	220
La Pietra	1/83–7/84	<i>inflation</i>	–178	17
75–50%	7/84–3/94	<i>deflation</i>	–171	26
	3/94–5/94	<i>inflation</i>	–1875	358
	3/00–3/01	<i>inflation</i>	7250	1089
Solfatara	6/83–1/85	<i>inflation</i>	–224	11
75–50%	1/85–2/89	<i>deflation</i>	–287	27
	2/89–7/89	<i>inflation</i>	–566	13
	3/00–3/01	<i>inflation</i>	–1142	153
Bagnoli	2/81–1/82	<i>deflation</i>	–956	261
50–25%	1/82–7/84	<i>inflation</i>	–174	24
	5/87–3/00	<i>deflation</i>	–143	57
	3/00–3/01	<i>inflation</i>	–12500	2600
Arco Felice	2/81–1/82	<i>deflation</i>	–800	130
50–25%	1/82–7/84	<i>inflation</i>	–193	40
	7/84–3/00	<i>deflation</i>	–123	27
	3/00–3/01	<i>inflation</i>	5200	688
Via Campana	2/81–1/82	<i>deflation</i>	–955	225
50–25%	1/82–7/84	<i>inflation</i>	–163	19
	2/93–3/00	<i>deflation</i>	126	143
<25% mvd				
Astroni	1/88–3/01	<i>deflation</i>	–748	351
Baia Castello	9/83–4/84	<i>inflation</i>	177	123
	1/91–3/01	<i>deflation</i>	–1415	950
Miseno	2/81–1/85	<i>inflation</i>	–294	23
	1/85–3/01	<i>deflation</i>	–339	498
Monte Ruscello	1/91–3/01	<i>deflation</i>	–486	1055
Nisida	7/84–3/01	<i>deflation</i>	1591	290
Piazza Esedra	1/83–7/84	<i>inflation</i>	–119	136
	7/84–3/01	<i>deflation</i>	1160	244
Posillipo Genemica	2/90–3/01	<i>deflation</i>	4867	1883
Quarto Stazione	2/81–1/85	<i>inflation</i>	–527	416
	1/85–3/01	<i>deflation</i>	216	125